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MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

DETERMINATION OF AIR-CONSUMPTION PARAMETERS FOR TWO RADIAL AIRCRAFT ENGINES

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SUMMARY

Air-consumption data from calibrations of two radial aircraft engines were analyzed to show the relation of engine air consumption to its primary influencing factors: intake-manifold pressure, exhaust back pressure, intake-manifold temperature, and engine speed.

The analysis of the test data from these two engines led to the establishment of a relation of variables upon which the design of automatic metering controls can be based. The results of this analysis also substantiate the conclusions presented in a similar published report. The data from one engine indicate that the air-consumption correlation obtained for this engine is accurate within ± 2 percent except under certain conditions that are well outside current engine-operation limits. This analysis and previous work done on other engines indicate that engines of the same general design tend to have similar pressure parameters. Investigations of each design of engine must be conducted, however, to make an accurate determination of the parameters affecting air consumption and the relation between them.

INTRODUCTION

At the request of the Air Technical Service Command, Army Air Forces, engine air-consumption data are being analyzed at the NACA Cleveland laboratory to show the correlation between the predominating variables that influence air flow and the manner in which these variables may be used as a basis for the design of automatic metering controls for aircraft engines.

Analyses of the air-consumption parameters for a XR-3350-4 engine and a R-2600-8 engine are presented in reference 1. The analysis presented herein, which is an extension of the evaluation of air-consumption parameters for automatic metering controls, has been made with data from engine A (R-2800-5) and engine B (XR-1820-42).

From the data of engine A a more detailed analysis of any limitations of the type of correlation presented herein was possible, inasmuch as the tests were specifically conducted for the effect of exhaust back pressure on engine performance and thus covered operation with a wider range of exhaust back pressures than were previously available. The limiting conditions are considered and evaluated.

The data for the analysis of engine A were obtained from NACA tests; the data from engine B were obtained from tests conducted at the Naval Air Material Center, Naval Air Experimental Station. Both of these engines are of the carburetor type.

METHOD OF ANALYSIS

The analysis presented herein has been made in a manner similar to the analysis of reference 1 in that only the following predominating factors that influence engine air consumption are considered: (1) intake-manifold pressure, (2) exhaust back pressure, (3) intake-manifold temperature, and (4) engine speed. Although the method of analysis and the results presented are very similar to those of reference 1, several additional graphs are presented in order to show the results more clearly.

The following symbols are used in the analysis:

p_m intake-manifold pressure measured at supercharger-case rim, inches of mercury absolute

p_e exhaust back pressure, inches of mercury absolute

t_m intake-manifold temperature, °F

N engine speed, rpm

W engine air consumption, pounds per cycle

K_n speed factor (deviation of air flow from reference speed)

ANALYSIS AND RESULTS

Parameters for Engine A

Results of the analysis of the data obtained from tests of engine A (R-2800-5) are presented in figures 1 to 5. This 18-cylinder engine has a bore of 5.75 inches, a stroke of 6.00 inches, a valve overlap of 40°, and a compression ratio of 6.65. The test work from which these data were obtained was so conducted as to control intake-manifold pressure, exhaust back pressure, and carburetor-air temperature. Under these conditions of operation, intake-manifold temperature varied considerably; therefore a correction to some reference temperature was necessary in order to correlate the data for the individual effects of intake-manifold pressure, exhaust back pressure, and engine speed. From the available data, curves of air flow were plotted against intake-manifold temperature at eight different constant conditions of speed, intake-manifold pressure, and exhaust back pressure. (See fig. 1). Linear curves of the same slope could be drawn through each set of data points in figure 1. The maximum deviation from the data points was less than 2 percent and, in most of the cases, less than 1 percent. The value determined for this slope was 0.00017 pound per cycle per °F. With this value the data were then corrected to a reference temperature of 150° F.

The variation of air flow with intake-manifold pressure at various exhaust back pressures and five constant speeds is shown in figure 2. Because it was desired to obtain a simple relation between the variables, linear curves of the same slope were drawn on each of the plots at exhaust back pressures of 10, 20, 30, 40, and 50 inches of mercury absolute. With the exception of certain points, which will be discussed later, those curves follow the data points relatively well. Because the linear curves in figure 2 can be drawn to the same slope, the change in air flow per inch change in intake-manifold pressure is the same for all speeds and exhaust back pressures. Examination of figure 2 shows that the spacing between each of the exhaust-back-pressure curves for each engine speed is equal but that the amount of this spacing decreases with an increase in engine speed; this decrease indicates that the change in engine air flow per inch change in exhaust back pressure decreases slightly with increasing engine speeds. This effect has been neglected because the error so introduced in the air-consumption correlation is only about 0.5 percent. A more detailed analysis of the effect of engine speed on the change in air flow with a change in exhaust back pressure is given in the appendix.

The following equation, which is obtained from figure 2(c), represents the air consumption at an engine speed of 2000 rpm and an intake-manifold temperature of 150° F:

$$W\begin{pmatrix}2000 \text{ rpm}\\ 150^\circ \text{ F}\end{pmatrix} = 0.000336\ (11\ p_m - p_e) - 0.0047 \qquad (1)$$

Although equation (1) is correct at all speeds with regard to slope, it requires a correction for the relative location of the various curves at the different speeds before it can be applied to speeds other than 2000 rpm. Figure 3, which is a replot of figure 2 at an exhaust back pressure of 30 inches of mercury absolute, was plotted to obtain this correction. A cross plot of figure 3, which is given in figure 4, indicates the required speed correction. Inasmuch as this correction is independent of intake-manifold and exhaust back pressures, the ordinate in figure 4 has been written as the deviation of air flow from the air flow at 2000 rpm.

When the temperature-correction factor and the speed correction are incorporated in equation (1), the following air-consumption relation is obtained for engine A at any intake-manifold pressure, exhaust back pressure, intake-manifold temperature, and engine speed:

$$W = 0.000336\ (11\ p_m - p_e) + 0.00017\ (150 - t_m) + K_n - 0.0047 \qquad (2)$$

The speed factor K_n in equation (2) is the ordinate in figure 4 for the particular speed at which the air consumption is desired.

The correlation between the actual engine air consumption and that computed from equation (2) is shown in figure 5. Figure 5(a) shows the correlation for exhaust back pressures from 28 to 32 inches of mercury absolute; figure 5(b) for exhaust back pressures from 7 to 28 inches of mercury absolute; and figure 5(c) for exhaust back pressures from 32 to 65 inches of mercury absolute. With the exception of some points at very low exhaust back pressures and some at very high exhaust back pressures, the computed and actual air flows are within ±2 percent. The points at low exhaust back pressures occur at engine speeds of 1800 rpm and below and at intake-manifold pressures greater than 40 inches of mercury absolute; the points at high exhaust back pressures occur when the ratio of intake-manifold pressure to exhaust back pressure is less than approximately 0.7. (See figs. 5(b) and 5(c).) Inasmuch as both of these conditions are outside the present engine operating range, they are not considered to limit the application of the correlation.

Parameters for Engine B

The test work, the method of analysis, and the results of the analysis of the data from the nine-cylinder engine B (XR-1820-42) are similar to those in reference 1 and are presented in figures 6 to 10. Engine B has a bore of 6.125 inches, a stroke of 6.875 inches, a valve overlap of 40°, and a compression ratio of 6.7. A reference temperature of 100° F was used rather than 150° F as in the engine A analysis inasmuch as it corresponded closer to the mean intake manifold temperature for the entire series of engine B tests.

The air consumption of engine B at any operating conditions can be calculated from the following equation:

$$W = 0.000525\,(5.33\,p_m - p_e) + 0.000125\,(100 - t_m) + K_n + 0.0044 \qquad (3)$$

The speed factor K_n in equation (3) is plotted in figure 9. Figure 10 shows the correlation between the actual air flow and the air flow computed from equation (3) for both sea-level and altitude conditions. Although the accuracy of the correlation between the computed and actual air flows at sea level is about ±2 percent, the difference in computed and actual air flow under altitude conditions is approximately ±4 percent.

Because so few data were available, it was not possible to determine the limiting conditions for engine B that were obtained for engine A.

DISCUSSION OF RESULTS

The better correlation obtained for the data from tests of engine A as compared with that obtained from the data of engine B is believed to be due to the variation in test methods used. The tests of engine A were specifically conducted to obtain the information required in this analysis and precautions were therefore taken to ensure that the test conditions were maintained and were those recorded. In addition, any questionable data were repeated and inconsistencies were thus further eliminated. The engine B data, on the other hand, were obtained from standard Navy calibration tests in which no special precautions such as the foregoing were taken. Furthermore, the purpose of the engine B tests was to determine operation of the power plant under present operating conditions. The tests were therefore not made over as wide a range of conditions as the engine A tests. Although this factor prohibited determining whether the ±4-percent spread in the correlation was caused by any limiting conditions, it is more likely that the spread resulted from the test method used. The precautions taken in the engine A tests seem to be necessary in order to obtain reliable data for an

air-consumption analysis. Correlations as satisfactory as those obtained for engine A could probably be obtained for any engine if the test conditions were as well controlled.

As stated in reference 1, any difference in pressure parameters between engines is believed to be caused by the difference in design of the cylinders and of the intake and exhaust systems. This statement is further substantiated by the similarity of the pressure parameters that have been computed for the XR-1820-42 (engine B), the R-2600-8 engine (reference 1), and XR-3350-4 engine (reference 1), which are engines of very similar construction, and the marked difference between these parameters and those obtained for the R-2800-5 engine, (engine A) which is of a different construction. The limitations of the available data do not permit a satisfactory analysis of the design features that exert the greatest influence.

Although the temperature correction is considered independent of the air flow per cycle, it is actually an average for the range of air flows that the particular engine handles. Inasmuch as engines of greater displacement consume greater quantities of air per cycle, the correction factor should increase with cylinder displacement. This trend is substantiated in the temperature-correction factors that have been determined for the engines analyzed.

SUMMARY OF RESULTS

The following results were obtained from an analysis of air-consumption data from tests of engine A (R-2800-5) and engine B (XR-1820-42):

1. The results of the analysis substantiate previous work in that equations were obtained which relate intake-manifold pressure, exhaust back pressure, intake-manifold temperature, and engine speed to engine air consumption and which can be used as the design basis for automatic metering controls.

2. The accuracy of the equation for engine A is within ±2 percent over the present engine operating range; indications are that similar accuracy can be obtained for any engine if careful techniques are used to obtain the air-consumption data.

3. Although engines of the same general design tend to have similar pressure parameters, individual calibration tests are necessary for each design.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 21, 1945.

APPENDIX - EFFECT OF ENGINE SPEED ON THE EXHAUST-BACK-PRESSURE CORRECTION

The magnitude of the error in engine air consumption in equation (2) caused by neglecting the change in the effect of exhaust back pressure with changes in engine speed is considered herein.

Inasmuch as equation (2) was calculated from figure 2(c), any air-consumption calculation at an engine speed of 2000 rpm will be that indicated on figure 2(c). For example, at an intake-manifold pressure of 34 inches of mercury absolute, an exhaust back pressure of 30 inches of mercury absolute, and an intake-manifold temperature of 150° F, figure 2(c) indicates an air flow of 0.1109 pound per cycle. This same value is obtained with equation (2). Similarily, any calculation at any other manifold conditions at an engine speed of 2000 rpm will correspond to that indicated on figure 2(c).

Furthermore, inasmuch as the speed correction K_n corrects conditions at an exhaust back pressure of 30 inches of mercury absolute, any air-consumption calculation at any speed and intake-manifold condition at an exhaust back pressure of 30 inches of mercury absolute will also correspond to that indicated by figure 2.

The discrepancy occurs in calculating the air flow at any speed other than 2000 rpm with exhaust back pressures other than 30 inches of mercury absolute. For instance, the air flow calculated from equation (2) at an intake-manifold pressure of 34 inches of mercury absolute, an exhaust back pressure of 30 inches of mercury absolute, an intake-manifold temperature of 150° F, and an engine speed of 2400 rpm is 0.1195 pound per cycle; whereas figure 2(a) indicates that it is 0.1187 pound per cycle. The difference between these values is 0.67 percent. At the same intake-manifold condition and engine speed but at an exhaust back pressure of 20 inches of mercury absolute, the air consumption calculated from equation (2) is 0.1161 pound per cycle whereas figure 2 shows that it is 0.1158 pound per cycle. The difference in this case is 0.26 percent. The error at an intake-manifold pressure of 45 inches of mercury absolute, an exhaust back pressure of 10 inches of mercury absolute, an intake-manifold temperature of 150° F, and an engine speed of 2400 rpm is found to be 0.56 percent.

In a similar manner, the error may be calculated at other engine operating conditions. The maximum error incurred in the engine operating range is 0.7 percent and occurs at low intake-manifold pressures when the air flow is very low.

REFERENCE

1. Shames, Sidney J.: Air-Consumption Parameters for Automatic Mixture Control of Aircraft Engines. NACA ARR No. E4I23, 1944.